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HOT ISOSTATIC PRESSING OF ALUMINUM ALLOY CASTINGS

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Garrett Turbine Engine Company
A Division of the Garrett Corporation

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The program documented in this final report was directed at identifying HIP parameters that would provide the greatest improvement in mechanical properties of A201 aluminum castings through closure of internal porosity. Program conclusions were:

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- HIP processing can significantly reduce porosity in A201 castings; the HIP pressure parameter is the critical influence, although an increase in time and/or pressure can provide slight improvements

- A 950°F/15 ksi/6 hours HIP cycle improved initial Grade C and Grade B materials to Grade A; post HIP tensile strength for both materials was equal to maximum material property and the HCF endurance limit was improved 8-12 ksi

- At HIP temperatures greater than 965°F, remelting of the eutectic phase along grain boundaries can adversely affect mechanical properties

- Reducing the standard solution anneal time by 70 percent had no impact on the mechanical properties of HIP processed materials

- Ultrasonic inspection techniques are not applicable for inspection of A201 castings; grain size and surface roughness affect signal output

SUMMARY

A NASC sponsored program evaluating the benefits of hot isostatic pressing (HIP) of A201 aluminum castings was conducted by The Garrett Turbine Engine Company, Phoenix, Arizona. The program was focused on assessing the impact of HIP in healing shrinkage porosity and the subsequent improvements in tensile and high cycle fatigue (HCF) properties. Material showing radiographic Grades B and C quality were taken from production-reject ATF3-6 turbofan engine front frames and HIPed at four HIP conditions. The HIP cycles evaluated defined temperature, time, and pressure parameters. Mechanical property testing and metallographic evaluations were used to determine the benefits of each cycle and identify the best HIP parameters. All HIP conditions tested showed improvements in radiographic quality and mechanical properties.

Tensile and HCF tests showed marked improvements in mechanical properties with closure of internal porosity. The initial Grade C material showed the greatest improvement in tensile properties. HCF results showed nearly a two-fold increase in the endurance limit when Grade C material is improved to Grade A by HIP. In addition to strength improvements, data scatter was significantly reduced after HIP.

The best HIP cycle tested utilized 950°F/15 ksi/6 hrs parameters. Radiographic Grades B and C materials HIPed at these conditions were consistently upgraded to Grade A. The 950°F/15 ksi/6 hrs HIP cycle is a commercially viable cycle that can significantly improve material properties and, thereby, increase salvage potential and extend the utilization of aluminum castings.

PREFACE

This document presents the final technical report for work performed by The Garrett Turbine Engine Company, a Division of The Garrett Corporation, under Contract N00019-79-C-0649 for the Naval Air Systems Command Department of the Navy, during the 16-month period which started in October 1979 and, except for the final report, ended in January 1981. The NASC project engineers on this program were R. Steskal, J. Collins and M. Valentine. The program was under the technical direction of G. S. Hoppin, Senior Supervisor - Advanced Materials. S. J. Vonk was Principal Investigator and K. W. Benn was Program Manager. Foundry technical input for the program was provided by Floyd Larson, AiResearch Casting Company.

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1.0 INTRODUCTION

A continuing problem in aluminum castings is the presence of internal shrinkage porosity, which can result from processing variables such as the geometric effects of the mold, or the effects of casting parameters including metal temperature, mold temperature, cooling rate, and pour rate. Process refinements can reduce porosity levels significantly, but are usually inadequate to completely eliminate the voids. Also, design restrictions often limit or hamper process modifications. Consequently, high reject rates and low or inconsistent material properties are frequently encountered.

A potential solution to the problem of internal porosity in castings is hot isostatic pressing (HIP). The HIP procedure involves the use of a uniform gas pressure applied at an elevated temperature. In the case of aluminum alloys, pressures to 15 ksi and temperatures to 980°F can be attained in commercial autoclaves. The applied pressure causes plastic flow in the material and a resultant healing of the internal porosity.

A potential benefit of the HIP operation is a reduction in mechanical property scatter and an overall improvement in mechanical properties. If the reliability and consistency of castings could be improved to the level of forgings, the more expensive forgings could be replaced with castings, or casting design wall thickness could be reduced, with resultant weight savings.

HIP has been commercially used for casting densification for several years and has a sound technological base for material property improvements. However, processing parameters generally are determined for a specific application, and generic processes have not been evaluated. To effectively utilize HIP for aluminum alloy castings, a clearer understanding of the processing parameters and resulting benefits is required.

The program documented in this report was conducted by Garrett for NASC (Contract N00019-79-C-0649) and was directed at identifying the HIP parameters that would provide the greatest improvement in mechanical properties through closure of internal porosity in A201 alloy aluminum castings. A correlation of processing parameters with tensile and high cycle fatigue (HCF) properties provided a sound basis for the identification of acceptable HIP conditions.

2.0 TEST MATERIALS

2.1 <u>Aluminum Alloy A201 - Background</u>

Aluminum alloy A201 (orginally designated as KO-1) is a cast alloy exhibiting good high-temperature strength, ductility and toughness. This alloy, developed by Conalco, Inc., is used for numerous aircraft structural components and gas turbine engine hardware.

The Aluminum Association registered compositions for A201 are shown in Table 1. The alloy modifications (202.0 and 202.2) are designed to improve remelt operations by adding chromium to lessen the dangers of "burning" or incipient melting during solution heat treatment. However, these modifications, result in decreased strength and ductility and are not as commonly used as the original alloy.

Alloy A201 is commonly produced by sand or chill casting, depending on application. Where large components are involved, the primary method is sand casting; for smaller more intricate parts, permanent mold, plaster, and investment casting processes are utilized.

The most common heat treatments for A201 are the T6 and T7 conditions. The T6 provides optimum mechanical properties, while the T7 (over-aged) condition provides a better balance of mechanical properties and corrosion resistance. Both heat treatments are artificial aging cycles. In the T7 heat treatment, following a solution treatment, the material is quenched in water to a temperature of 140 to 180°F, and then stabilized at ambient temperature for 12 hours. A final artificial, or accelerated, aging is accomplished by a 365 to 375°F treatment for 5 hours with an air cool. The T6 treatment is identical with the exception of the aging treatment temperature, which is 330 to 340°F.

TABLE 1. ALUMINUM ASSOCIATION CHEMICAL COMPOSITIONS FOR A201 AND MODIFIED A201 (202)

Alloy Designation	Product	Percent by Weight of Elements								
		Si	Fe	Cu	Mn	Mg	Cr	Ti	Ag	Al
A201.0	Sand Cast	0.05	0.10	4.0-5.0	0.20-0.40	0.15-0.35	--	0.15-0.35	0.4-1.0	Bal
A201.2	Ingot (Chill Cast)	0.05	0.07	4.0-5.0	0.20-0.40	0.20-0.35	--			
202.0	Sand Cast	0.10	0.15	4.0-5.2	0.20-0.8	0.15-0.55	0.20-0.6			
202.2	Ingot (Chill Cast)	0.10	0.10	4.0-5.2	0.20-0.8	0.20-0.55	0.20-0.6			

Typical mechanical properties for A201-T7 castings are shown in Table 2. The ranges indicated may be the result of casting process variations and, therefore, sensitive to the HIP operation.

2.2 Material Requirement

Two types of A201 alloy castings, exhibiting a minimum of two radiographic quality grades, were required for the test program. Production requirements for gas turbine components typically establish a minimum radiographic quality of Grade B. Therefore, it was necessary to procure a second test material exhibiting a radiographic grade of C or lower to provide a comparison to the production quality material.

2.2.1 Procurement of Test Materials

The test materials for this program were to be obtained from AiResearch Casting Company in Torrance, CA. The plan was to cast rectangular test blocks with specified levels of internal porosity. The blocks were designed to facilitate test specimen preparation and required no machining prior to HIPing. This latter point was considered important since any machining operation could expose subsurface porosity, and subsequent HIPing would be ineffective in closing the holes, since HIPing is effective only in closing internal porosity.

TABLE 2. TYPICAL MECHANICAL PROPERTIES OF A201-T7 CASTINGS

Ultimate Tensile Strength	62-67 ksi
Yield Strength	49-54 ksi
Elongation	1-9%
HCF Endurance Limit (10^7 cycles)	16-18 ksi

The initial attempts to prepare the required aluminum castings with controlled levels of porosity centered on chill casting. This technique is the process most commonly used for small aluminum alloy gas turbine components. A high degree of control is provided for casting parameters such as pour temperature, mold temperature, cooling rate, and riser and gating design.

Blocks were cast incorporating several variations in process parameters. These variations included two cooling rates, two pour temperatures, mold temperature changes from $<75°F$ to $>700°F$, and several iterations of gating. Parameters were individually and collectively evaluated in an effort to maximize casting porosity. In each instance, radiographic inspection identified porosity levels of Grades A or B. However, since a prior Garrett IR&D Program indicated only slight tensile strength differences between Grade A and B materials, the porosity levels obtainable by chill casting were considered insufficient for this program.

The inability to produce materials with *significant* levels of porosity in the test blocks designed for this program does not preclude shrinkage porosity in production aircraft engine components. As previously noted, the 12 x 3 x 1 inch test block design was established to facilitate specimen preparation. This simple configuration avoids many casting difficulties that promote porosity. Many production castings, however, exhibit a significant rejection rate as a result of localized shrinkage porosity.

When chill casting proved inadequate for the program effort, preparation of test blocks by sand casting was attempted. Presumably, sand casting would increase porosity within the casting by altering cooling rates. However, the block configuration continued to negate casting factors that otherwise would result in internal porosity. Ten test blocks were prepared with variations in risers and pour temperatures. All castings were determined to be radiographic Grade B.

Following the failures to produce porous castings by chill or sand casting of the rectangular test blocks, a search was made for production components that could provide the required material. The only component exhibiting sufficient porosity (radiographic Grade C) in great enough quantities to provide the necessary test specimens was the ATF3-6 turbofan engine front frame, (Figure 1). The ATF3-6 engine (Figure 2) is the primary power plant for the HU-25 Coast Guard aircraft. Five front frames rejected for porosity were located at Garrett. The only drawback in using these production reject front frames was the necessity to machine test material from the frames outer rims. The machining operation provided a possibility of interconnected internal porosity being exposed to the surface. Since no other convenient alternatives were available, this risk was accepted and the production components were utilized.

A benefit from the use of the ATF3-6 front frame for this program was the direct applicability of program results to production operations. This component is presently HIPed in production, and the results of the program will be used to refine and/or improve HIP parameters.

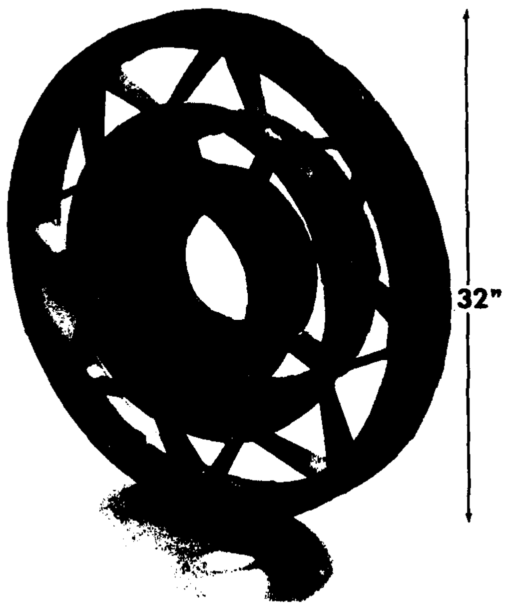

Figure 1. ATF3 turbofan engine front frame.

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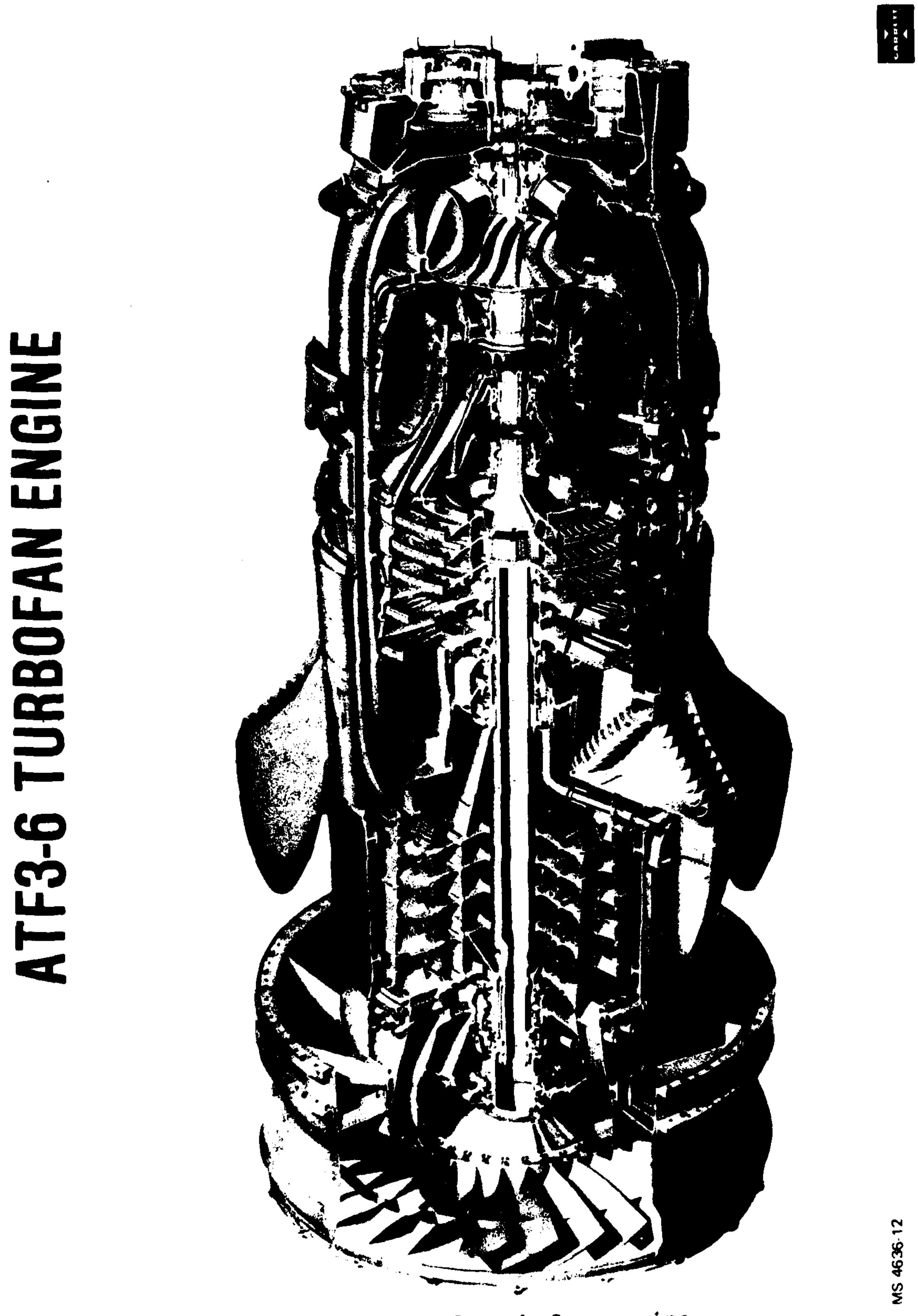


Figure 2. ATF3-6 turbofan engine.

3.0 PROCEDURES

3.1 Nondestructive Evaluation (NDE)

Nondestructive evaluation (NDE) techniques were utilized to assess internal porosity and establish control samples with known porosity size and distribution. X-ray inspection, which is the present production process for inspecting castings, was the primary technique utilized for screening and classifying the materials for this study. Pulse-echo ultrasonic inspection also was performed to evaluate the potential of this procedure for assessing porosity in aluminum castings.

3.1.1 X-Ray Inspection

To accurately classify all materials used in this program, radiographic inspection was utilized to identify and measure internal porosity. The inspections conformed to ASTM E155-60T (Garrett EMS 52348) for inspection procedures. The grading of the castings was based on Garrett EMS 52300, which defines allowable defect levels in a casting (Ref. ASTM E192-62T and E155-60T). The grading was solely based on porosity content of the material and did not attempt to identify other defects that would not be influenced by HIP. Radiographic grades are stated as A, B, C, or D, with A being the most sound and D denoting extremely large porosity.

In addition to the original classification used to locate material with specific porosity levels, X-ray inspection was used to assess the reduction of porosity in each HIP cycle. Following the HIP cycles, the test pieces were X-rayed a second time using identical parameters. The sections were reclassified and compared to the original inspection reports. The X-ray evaluation results for the HIP-processed ATF3-6 front frame material are shown on Table 3. Porosity was reduced and the radiographic

TABLE 3. RADIOGRAPHIC GRADING OF TEST SPECIMENS BEFORE AND AFTER HIP

HIP Cycle, °F/ksi/hr	Sample Frame/ Section No.	As-Cast Radio- graphic Grade*	Post-HIP Radio- graphic Grade*
950/10/6	2v8	B	B+/A-
	3v13	B	B+/A-
	1v2	C	B-/B
	3v3	C	B
950/15/6	4v5	B	A
	5v5	B	A-/A
	3v12	B	A
	5v10	B	A
	2v18	B	A
	1v1	C	B/B+
	3v4	C	A
	1v10	C	A
	2v1	C	A
	2v6	C	A
	2v10	C	A
980/10/6	1v4	B	A-/A
	4v6	B	B+/A-
	1v5	C	B/B+
	3v5	C	B+
950/10/12	5v3	B	B+/A-
	5v6	B	B+/A-
	1v7	C	B
	3v2	C	B/B+

*Radiographic grade was solely determined for porosity. Other factors, such as surface defects and plaster inclusions that are not influenced by HIP, were not considered.

grade was raised for every piece. The degree of improvement varied with HIP parameters and initial porosity level.

3.1.2 Ultrasonic Inspection

Machined blocks with 0.250-, 0.125- and 0.060-inch flat-bottomed holes 0.035-inch high, located in the interior of the samples, were inspected by the pulse-echo ultrasonic technique. A typical scan is shown in Figure 3. The holes are clearly identifiable, and no background interference is evident.

A further evaluation of this technique was conducted on a chill-cast test block, as shown in Figure 4. The two scans, taken on the same block, demonstrate significant variation in defect content. This is the result of several factors. Surface roughness and cast grain structure result in increased scatter of the ultrasonic pulse, leading to the appearance of internal defects (e.g., porosity) where none actually exist. The conclusion from this brief evaluation was that the present ultrasonic techniques are too sensitive to material surface roughness, and therefore, not capable of identifying internal porosity in cast aluminum structures.

3.2 HIP Cycles

This program was conducted in two phases to optimize the information obtainable from a limited number of HIP cycles. The first phase conducted and analyzed four HIP cycles, with variations in pressure, temperature, and time. The second phase utilized the most promising of the Phase 1 HIP cycles. Heat treatment modifications were evaluated in conjunction with the final HIP cycle. The Phase 2 cycle also provided sufficient data to conduct a statistical analysis of the mechanical properties developed under the Phase 2 HIP parameters.

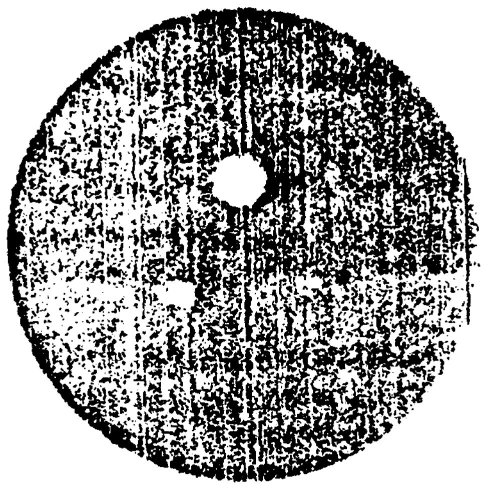


Figure 3. Pulse-echo ultrasonic scan of machined control block with 0.250-, 0.125-, and 0.060-inch diameter by 0.035-inch deep, flat-bottomed holes prior to HIP.

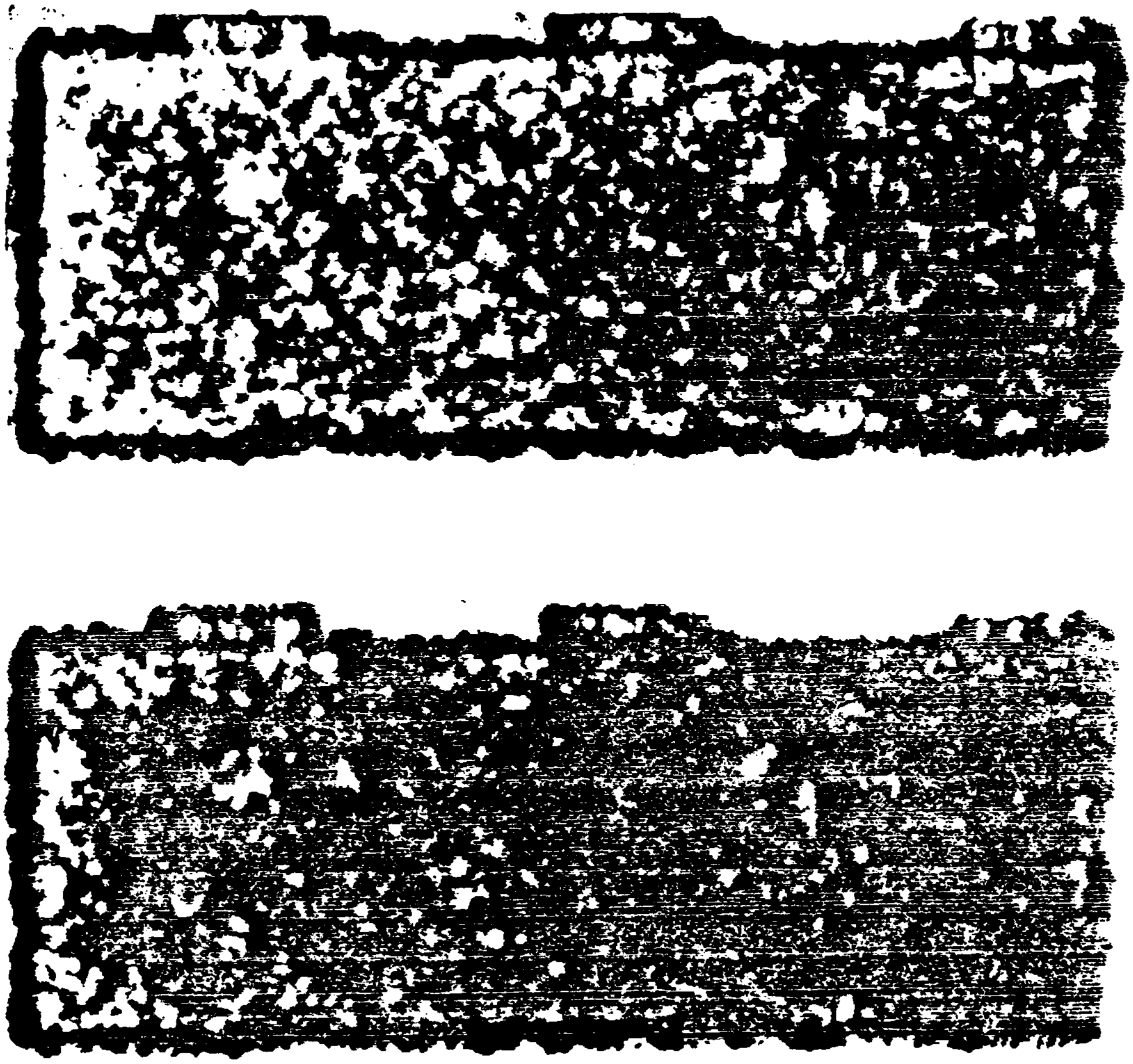


Figure 4. Pulse-echo ultrasonic scans of A201 chill-cast test block, radiographic Grade B. (Apparent variation in soundness results from surface roughness and grain structure. No correlation with X-ray results.)

The HIP parameters defined for the initial evaluation are shown in Table 4. The processing was performed at Industrial Materials Technology, Inc. (IMT) in their 24 x 7 inch diameter autoclave (No. 2), where virgin argon gas was used for pressurization. The HIP parameters were determined after consultation with personnel at IMT and Conalco (the developer of A201). Present ATF3-6 front frame production specifications require that HIPing operations be conducted with the parameters of HIP Run No. 1 (Table 4). Since previous work indicated that these conditions did not provide full closure of internal porosity, only higher temperatures and pressures or longer times were considered. The upper temperature limit was established at 980 ±10°F after Conalco indicated eutectic melting had been observed at 995°F. The 15-ksi pressure and 12-hour time parameters were selected to provide a large parameter change from the baseline conditions.

Based on mechanical property improvements observed during the Phase 1 HIP cycles (Section 4), the 950°F/15 ksi/6 hr cycle was selected for the Phase 2 HIPing. The HIP unit used in Phase 2 was the same as for the original cycles. The material HIPed included all remaining Grade C material and sufficient Grade B material to fill all available space in the autoclave.

3.3 Heat Treatment

A standard T7 heat treatment condition was established after each HIP cycle. This heat treatment provides the best combination of high-temperature mechanical properties and corrosion resistance. In addition, this is the specified heat treatment for the ATF3-6 front frame material used for this evaluation. The specific heat treatment schedules for the material from each HIP cycle are shown in Table 5. To assess the HIP cycle contribution toward the solutionizing stage of the heat treatment, the solution treatment time was significantly reduced for half the material from HIP cycle 5.

TABLE 4. HIP PARAMETERS FOR INITIAL FOUR RUNS

Run No.	Temperature, °F	Pressure, ksi	Time, hr
1	950 ±10	10.0	6
2	950 ±10	15.0	6
3	980 ±10	10.0	6
4	950 ±10	10.0	12

TABLE 5. HEAT TREATMENT SCHEDULES FOR HIPed MATERIAL

HIP Cycle	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
	Solution Treatment			Quench	Aging Treatment		Quench
1	940°F/2 hrs	970°F/2 hrs	980°F/6 hrs	WQ	Room Temp/12 hrs +	370°F/5 hrs	Air Cool
2							
3							
4							
5a							
5b	940°F/30 min	970°F/30 min	980°F/2 hrs				

4.0 *RESULTS*

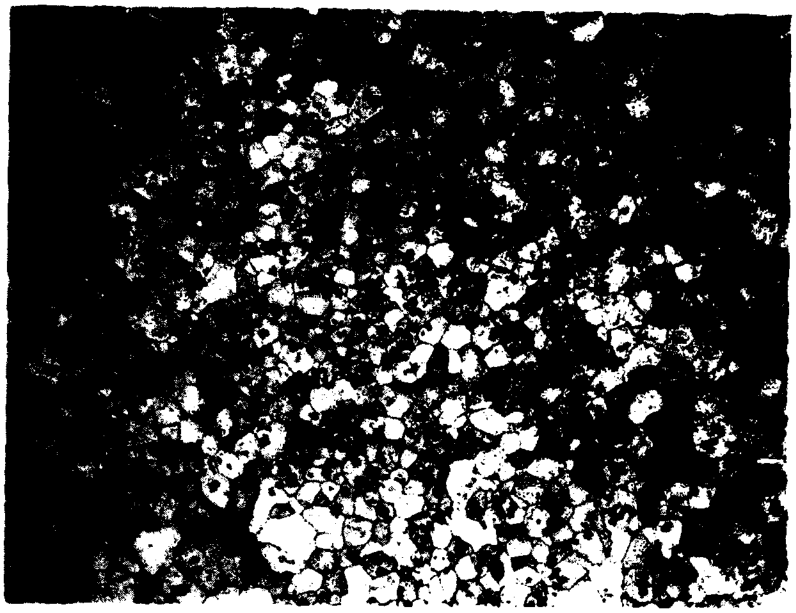
4.1 Metallographic Evaluation

A metallographic evaluation utilizing optical metallography and scanning electron fractography was conducted for each material section used in this program. These evaluations characterized material structures and fracture modes and related them to mechanical properties.

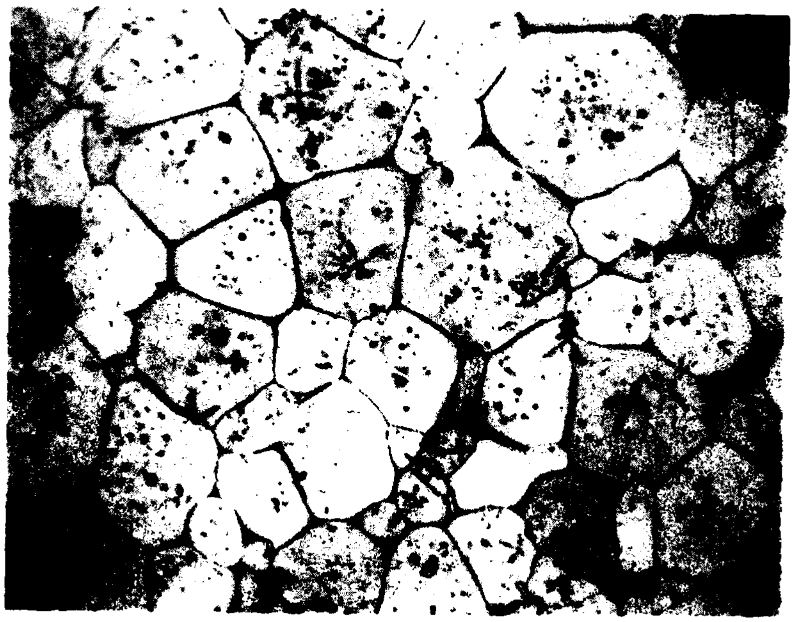
4.1.1 Optical Metallography

Optical metallography was performed on all material HIPed in this program, and on the as-cast material. Typical material structures, representative of the initial radiographic Grades B and C materials in the as-cast and HIPed condition, are shown in Figures 5 through 11. In every case, the material had been heat treated to the T7 condition.

A wide range of grain size is seen for the castings studied. Grain diameters range from 0.002 to 0.060 inches. In most instances, both extremes can be seen in the same material. Since all specimens received the same heat treatment and the HIP cycles were at or below the heat treat temperature, the variations seen probably are the result of casting/solidification differences. This would be a reasonable conclusion since conditions contributing to porosity in the material would be expected to affect grain structure as well. Specific casting operation influences are particularly obvious when comparing the Grade C material in the as-cast and HIP conditions [Photo (b) in Figures 5 through 9]. The as-cast sample grain size is significantly different from the HIP processed material, yet no relationship to HIP parameters is apparent.



1v8 (a)



1v3 (b)

Figure 5. Typical microstructure of as-cast A201-T7 material: (a) radiographic Grade B (b) radiographic Grade C. Keller's etch (50X).

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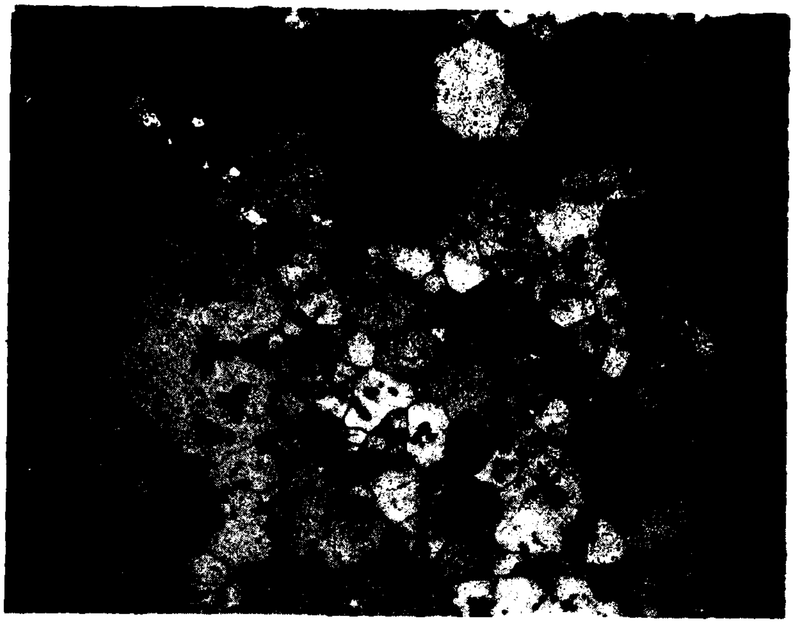
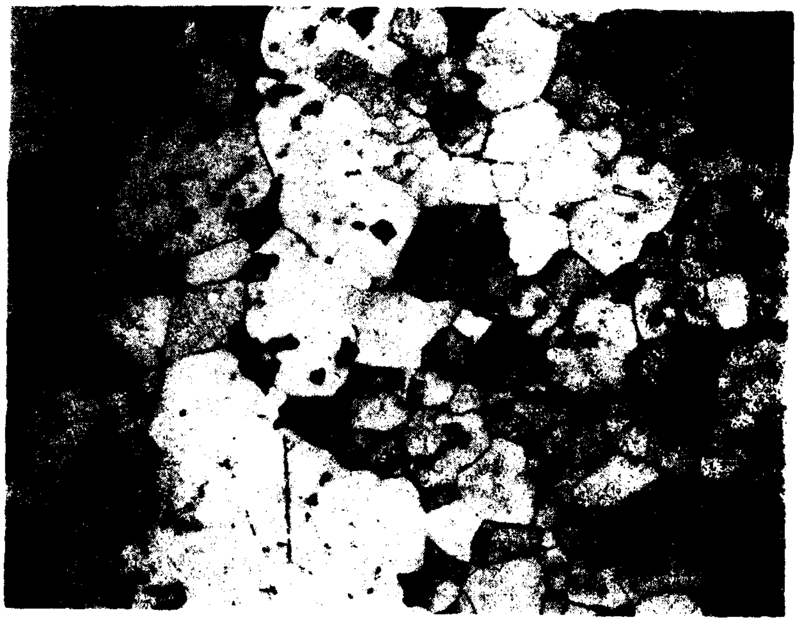


3v13 (a)



3v3 (b)

Figure 6. Microstructures of A201-T7 castings HIPed at 950°F/10 ksi/6 hr: (a) initial radiographic Grade B, post-HIP Grade B+/A-; (b) initial radiographic Grade C, post-HIP Grade B; Keller's etch (50X).

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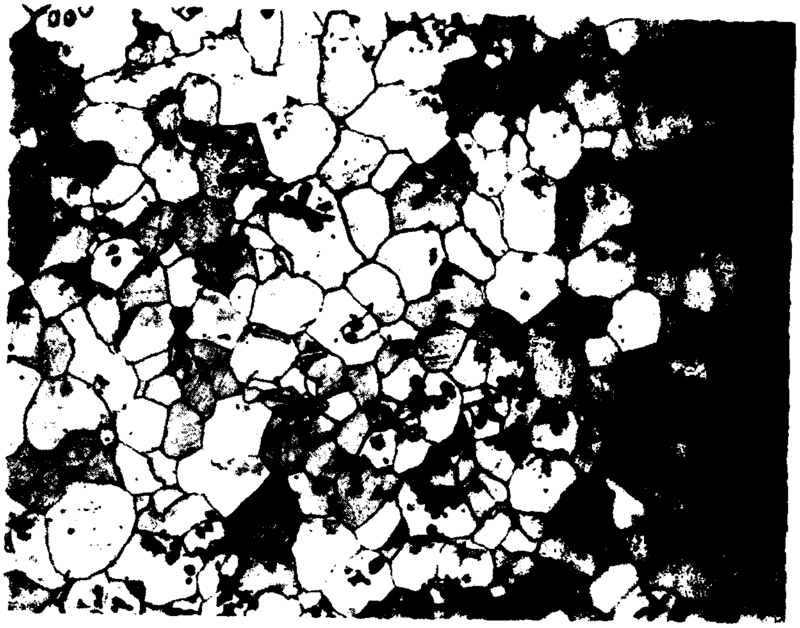

4v5 (a)

1v1 (b)

Figure 7. Microstructures of A201-T7 castings HIPed at 950°F/15 ksi/6 hr: (a) initial radiographic Grade B, post-HIP Grade A; (b) initial radiographic Grade C, post-HIP Grade B/B+; Keller's etch (50X).

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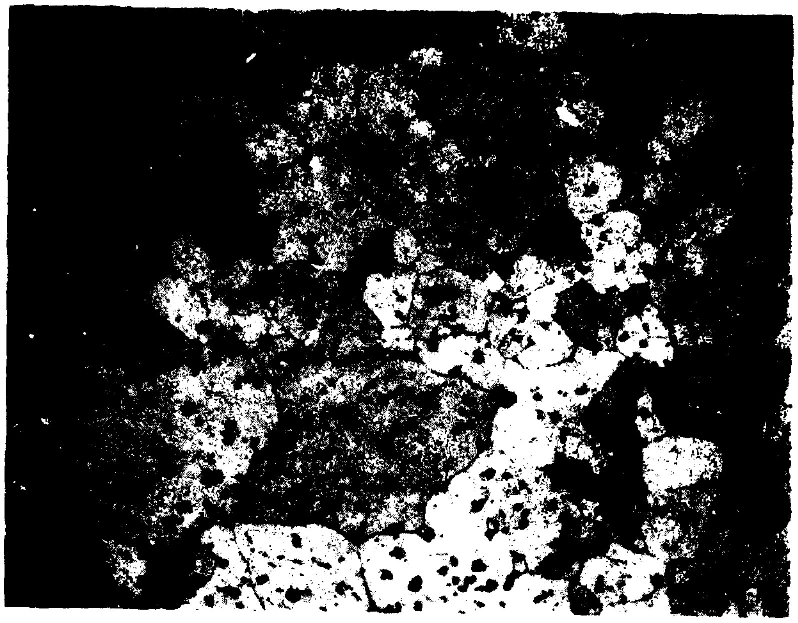

4v6 (a)

1v5 (b)

Figure 8. Microstructures of A201-T7 castings HIPed at 980°F/10 ksi/6 hr: (a) initial radiographic Grade B, post-HIP Grade B+/A-; (b) initial radiographic Grade C, post-HIP Grade B/B+; Keller's etch (50X).

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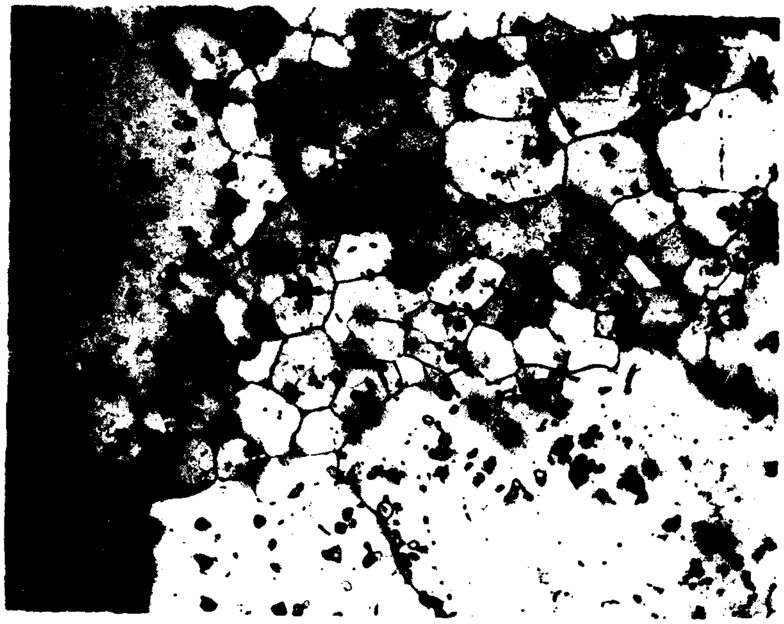
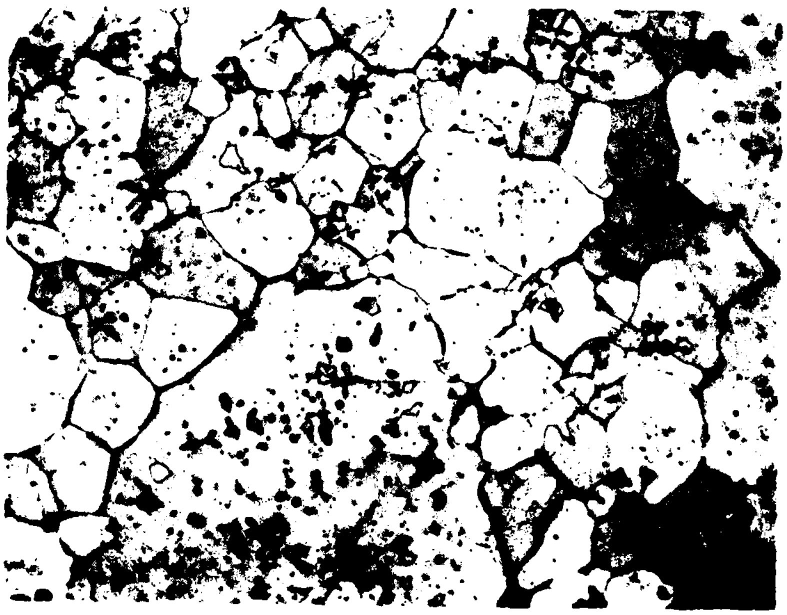


5v3 (a)



1v7 (b)

Figure 9. Microstructures of A201-T7 castings HIPed at 950°F/10 ksi/12 hr: (a) initial radiographic Grade B, post-HIP Grade B+/A-; (b) initial radiographic Grade C, post-HIP Grade B; Keller's etch (50X).

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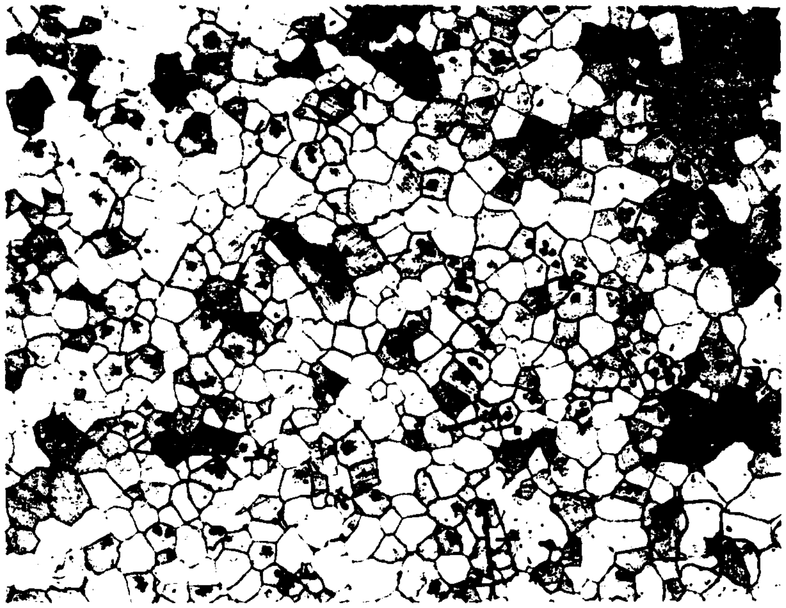
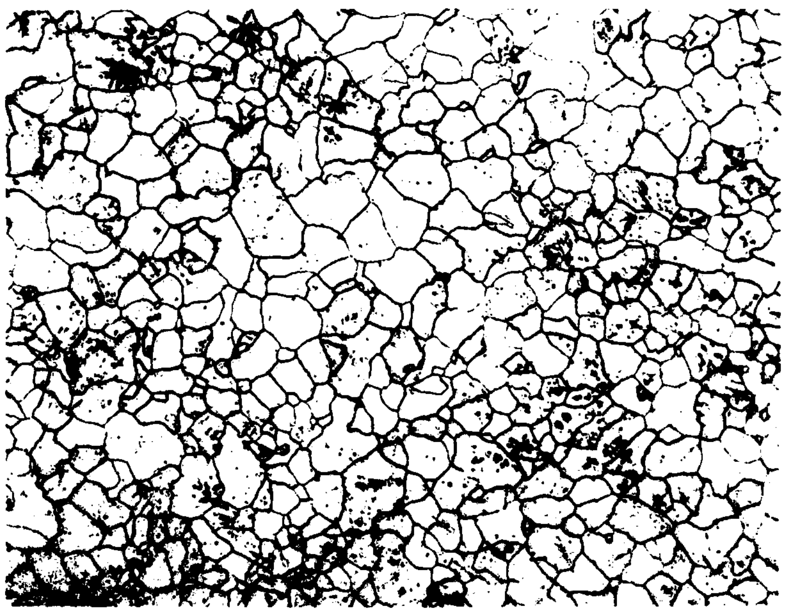


2v18 (a)



5v10 (b)

Figure 10 Microstructures of initial radiographic Grade B, post-HIP Grade A A201-T7 castings HIPed at 950°F/15 ksi/6 hr. The solution anneal used for the T7 heat treatment was: (a) 940°F/2 hr + 970°F/2 hr + 980°F/6 hr; (b) 940°F/30 minutes + 970°F/30 minutes + 980°F/2 hr. Keller's etch (50X).

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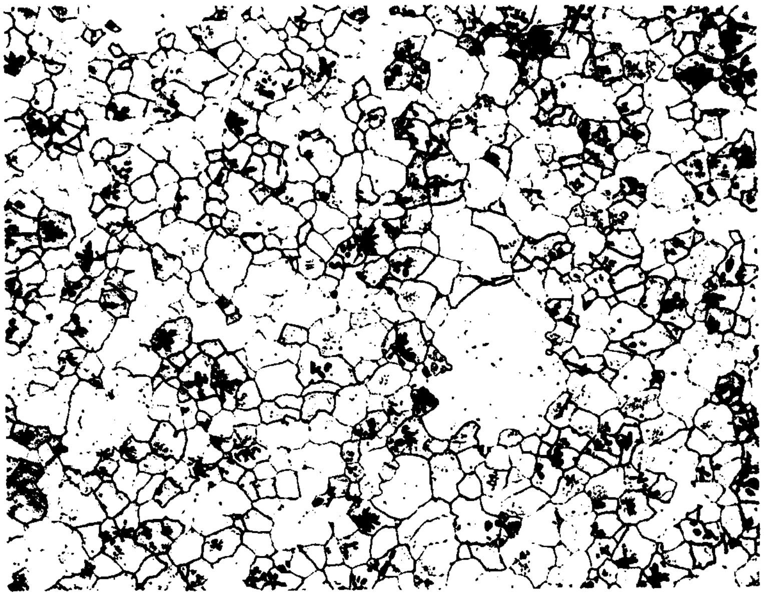

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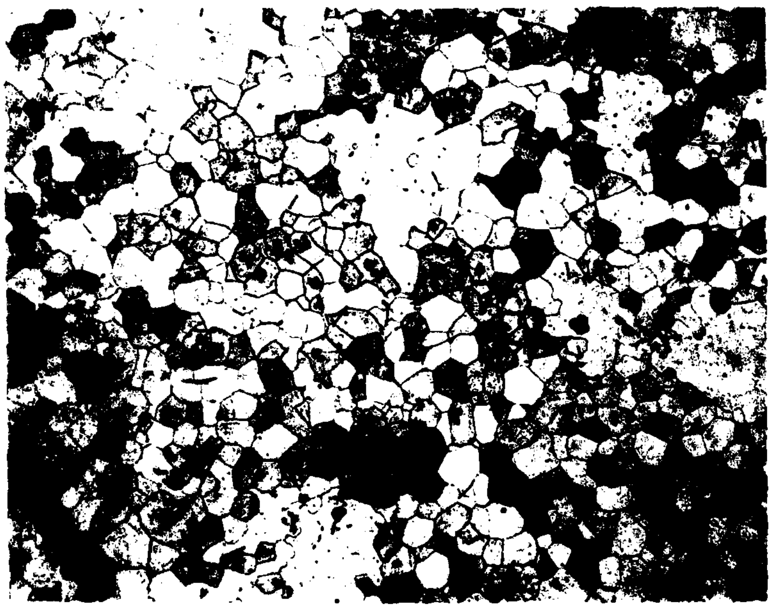


2v10 (b)

Figure 11 Microstructures of initial radiographic Grade C, post-HIP Grade A A201-T7 castings HIPed at 950°F/15 ksi/6 hr. The solution anneal used for the T7 heat treatment was: (a) 940°F/2 hr + 970°F/2 hr + 980°F/6 hr; (b) 940°F/30 minutes + 970°F/30 minutes + 980°F/2 hr. Keller's etch (50X).

Coring (the chemical inhomogeniety associated with non-equilibrium solidification) is denoted by the "flowers" distributed throughout the structure. Although the quantity of coring varies from sample to sample, it does not appear to be related to the thermal treatment received either in the HIP cycles or in the T7 heat treatment. This is of importance since homogenization times up to 22 hours are experienced when time at temperature is totalled for HIP and heat treat cycles.

A further casting process artifact observed in the metallographic sections was the eutectic phase found along some (but not all) grain boundaries in each of the Grade C material samples. No evidence of this eutectic phase was seen in the Grade B material. The eutectic phase has an influence on mechanical properties, but was critical only in the material processed in the 980°F HIP cycle. Figure 7(b) shows the eutectic phase along several grain boundaries in material HIPed at 950°F/15 ksi/6 hr; however, excellent mechanical properties were observed. A remelting of this phase appears to be required for a subsequent reduction in strength.

A direct comparison of microstructures developed through heat treatments utilizing different solutionizing times was undertaken to more clearly assess the contribution of the HIP cycle in homogenization and the criticality of complete homogenization for maximum mechanical properties. Figures 10 and 11 depict materials solutionized per the two time variations discussed in Section 3.3. As can be seen, the reduced solution time (3 hours instead of 10 hours) did not adversely affect homogeneity, phase distribution, or grain structure.

The importance of this observation is the implication for a potential reduction in the furnace operations required for production components. Significant time, cost, and energy savings

could be realized if the HIP cycle could replace or reduce the solution treatment phase of the final heat treatment.

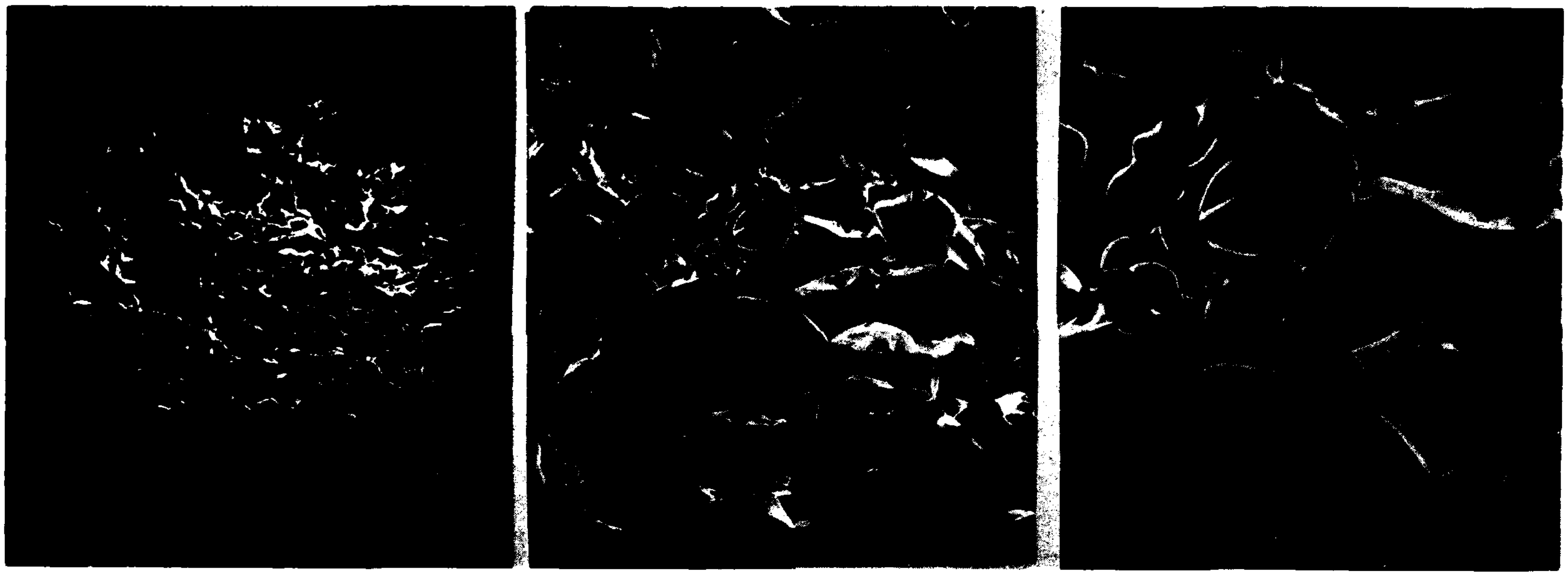
4.1.2 Scanning Electron Fractography

Fractography, utilizing a scanning electron microscope (SEM), was conducted on selected tensile fractures. Fractographs of particular interest are shown in Figures 12 through 19. The fracture modes vary greatly from ductile-rupture, to cleavage, to intergranular. Data from this evaluation are difficult to analyze as a result of the mixed-mode failures, but some trends are apparent.

The as-cast initial Grade C material exhibited grain boundary fractures predominantly (Figure 12). On close examination, it can be seen that the grain boundaries contain extensive porosity with only intermittent regions of metallurgical bonding. These well-bonded regions show a mixture of ductile-rupture and cleavage fracture modes. The extensive porosity along grain boundaries accounts for the low tensile strength of this material.

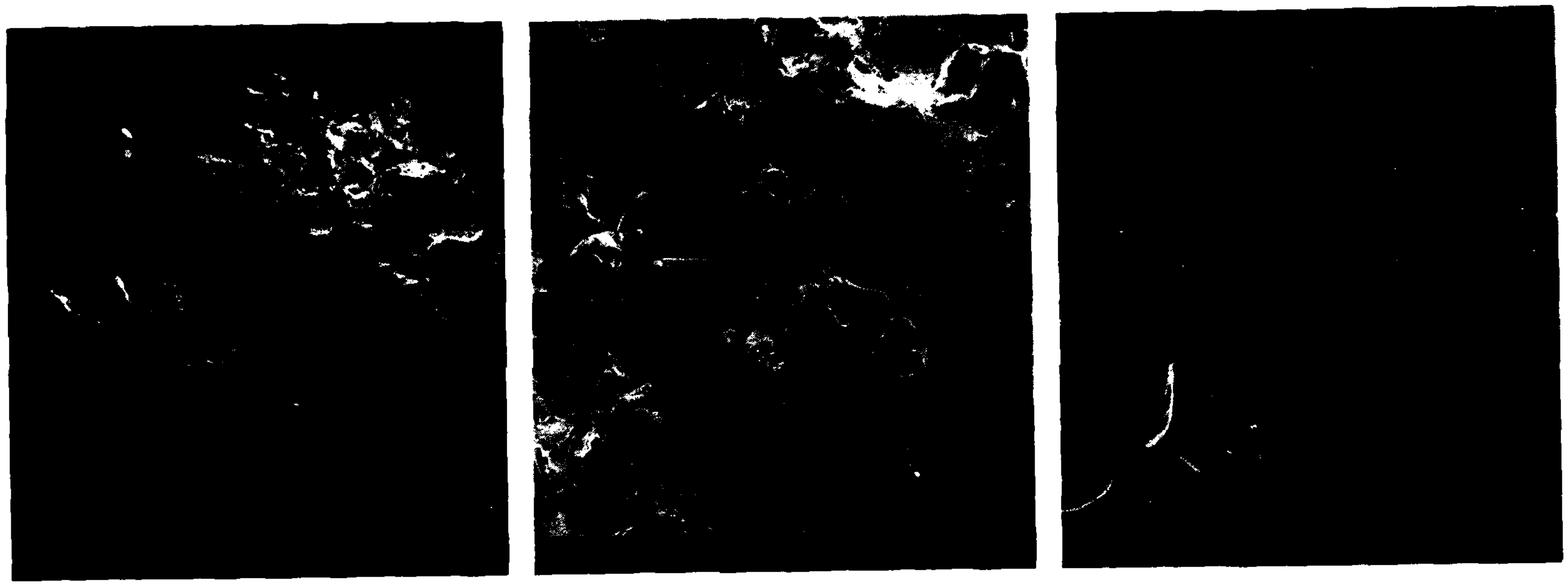
Fractographs of the initial Grade C material HIPed at 950°F/10 ksi/6 hr (Figure 13) indicate a significant reduction in porosity on the fractured surface. The almost continuous well-bonded regions result in the predominantly ductile-rupture failure mode exhibited. As expected, this material demonstrated significantly higher tensile strength.

A comparison of Figures 14, 15 and 16 shows the impact of eutectic melting. Figure 14 depicts the fracture surface associated with a high-strength fracture. The failure mode is essentially 100-percent ductile-rupture. However, a second test on an identical tensile bar from the same rim section shows a completely different failure (Figure 15). Much of the fracture surface is



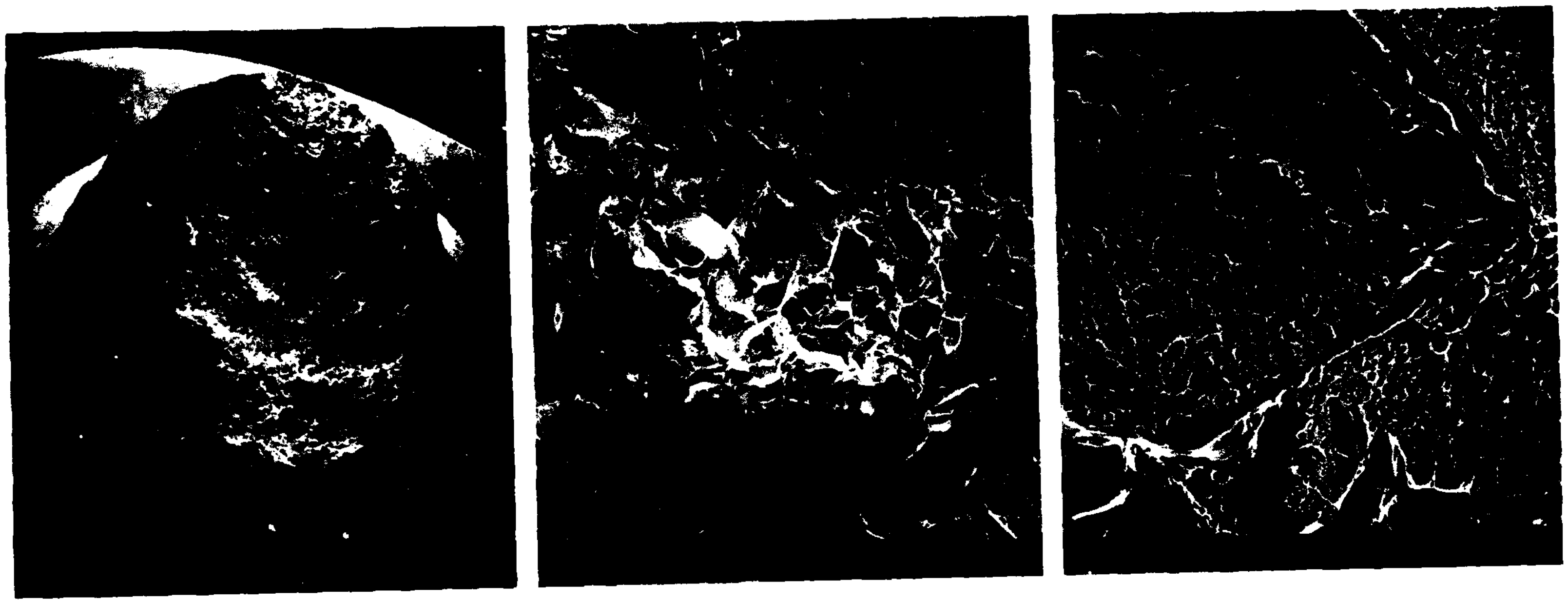
1v6-2 (a) 1v6-2 (b) 1v6-2 (c)

Figure 12. SEM fractographs of A201-T7 tensile bar that failed at 11.1 ksi. Material is as-cast radiographic Grade C.



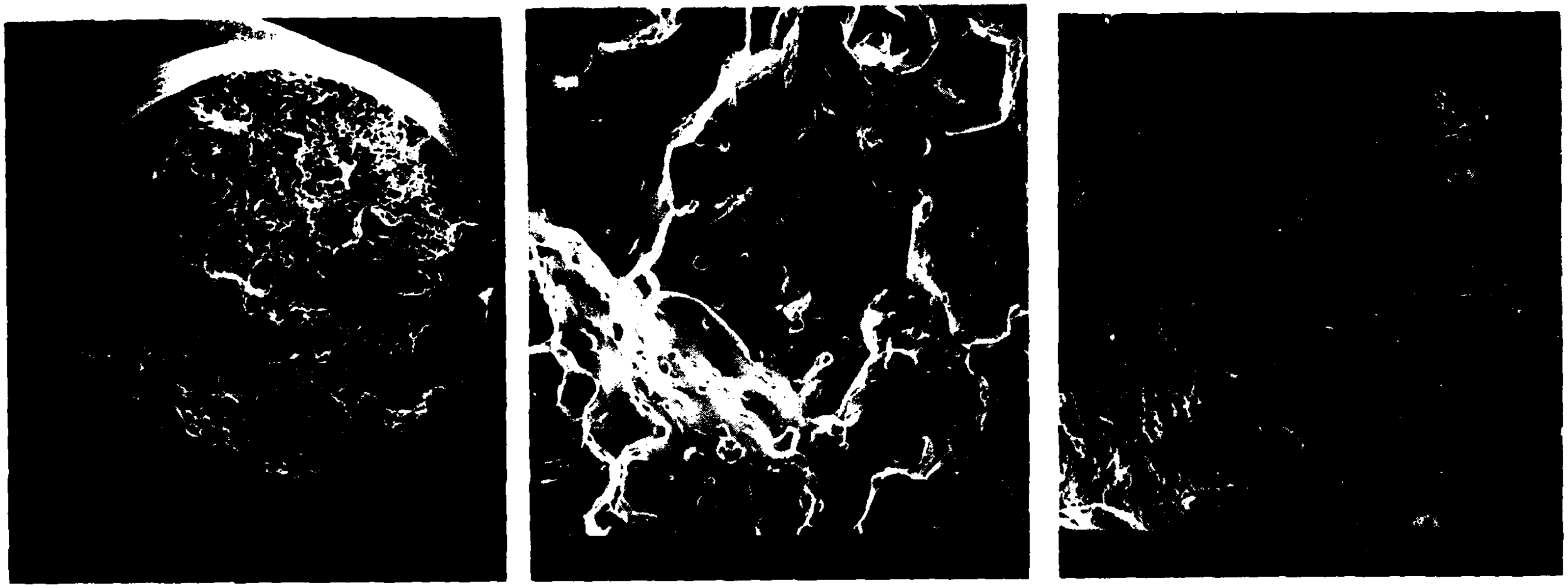
lv2-2 (a) lv2-2 (b) lv2-2 (c)

Figure 13. SEM fractographs of A201-T7 tensile bar that failed at 46.6 ksi. Material was HIPed at 950°F/10 ksi/6 hr. Initial radiographic Grade C, post-HIP Grade B.



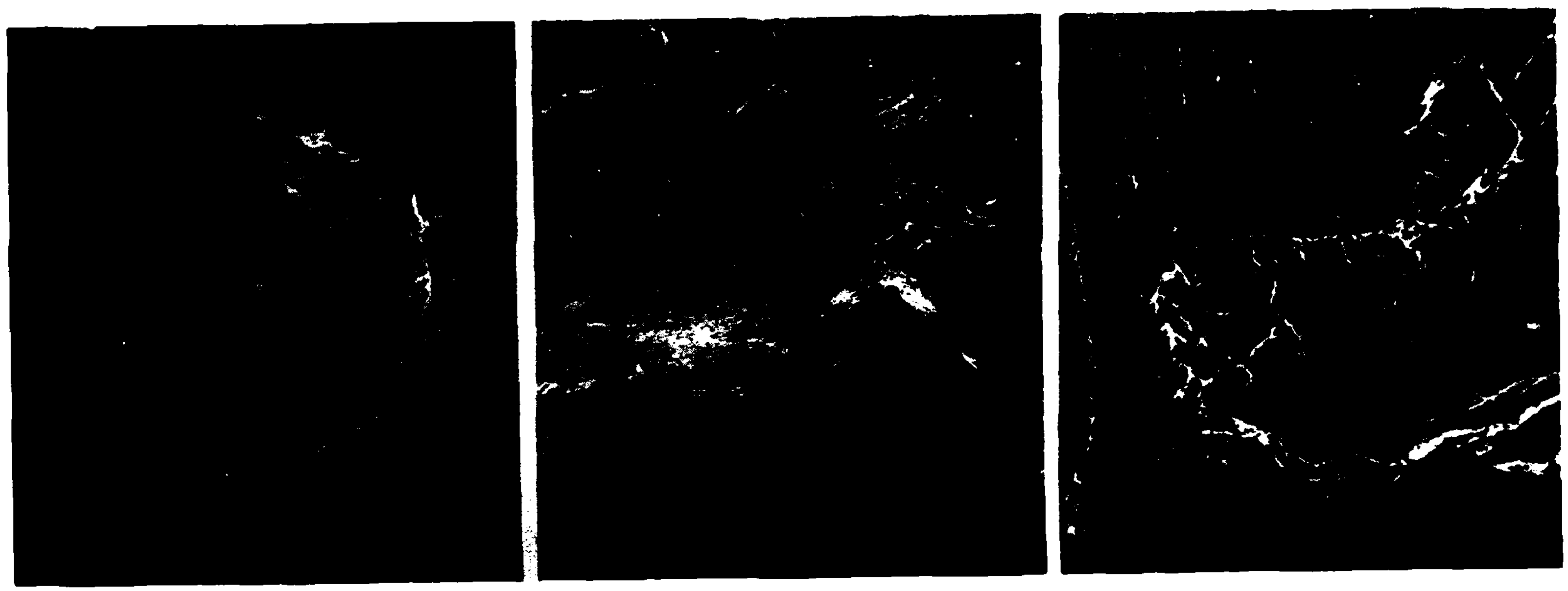
4v6-2 (a) 4v6-2 (b) 4v6-2 (c)

Figure 14. SEM fractographs of A201-T7 tensile bar that failed at 60.0 ksi. Material was HIPed at 980°F/10 ksi/6 hr. Initial radiographic Grade B, post-HIP Grade B+/A-.



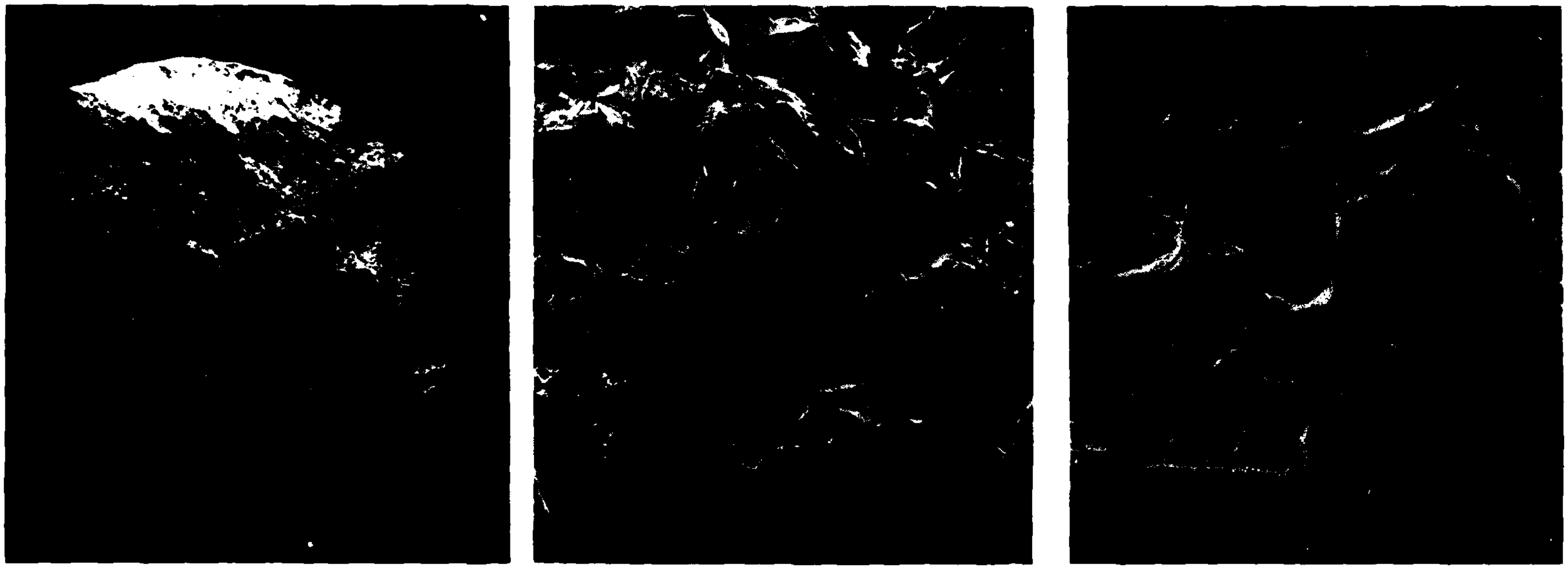
4v6-1 (a) 4v6-1 (b) 4v6-1 (c)

Figure 15. SEM fractographs of A201-T7 tensile bar that failed at 6.4 ksi. Material was HIPed at 980°F/10 ksi/6 hr. Initial radiographic Grade B, post-HIP Grade B+/A-.



3v5-1 (a) 3v5-1 (b) 3v5-1 (c)

Figure 16. SEM fractographs of A201-T7 tensile bar that failed at 45.4 ksi. Material was HIPed at 980°F/10 ksi/6 hr. Initial radiographic Grade C, post-HIP Grade B+.

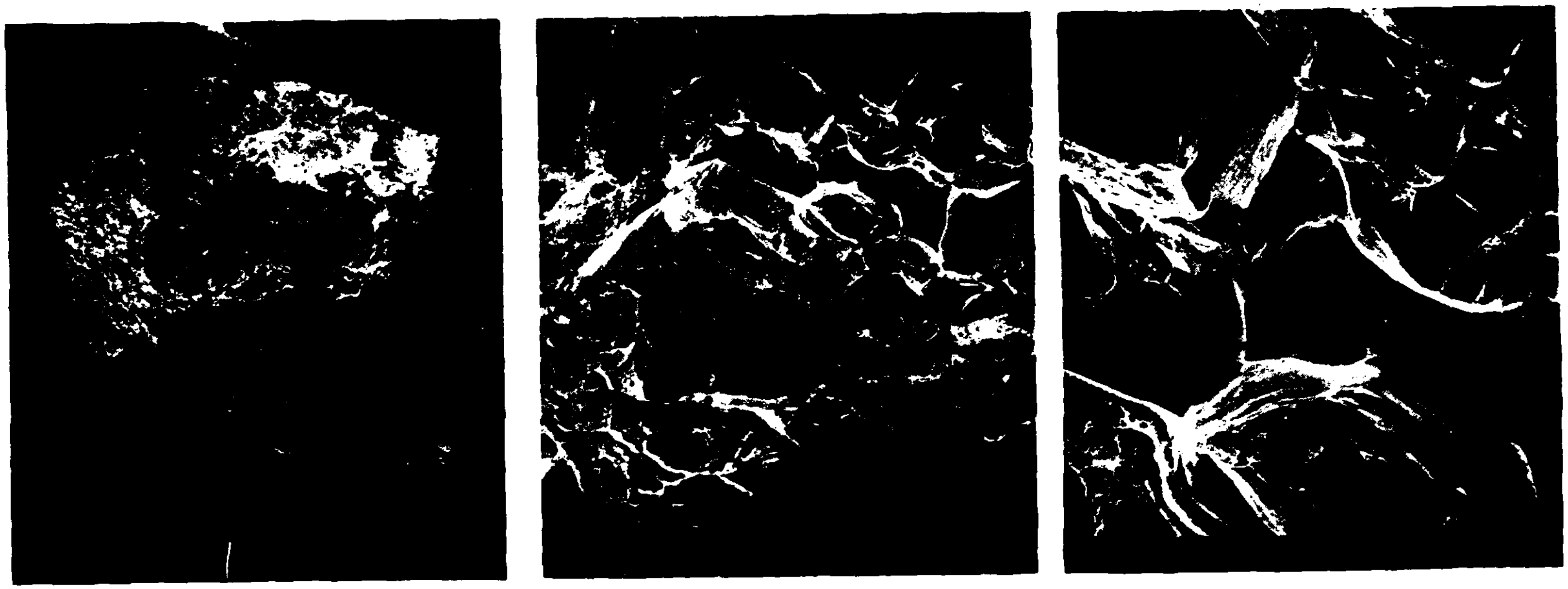


4v5-1 4v5-1 4v5-1

Figure 17. SEM fractographs of A201-T7 tensile bar that failed at 63.1 ksi. Material was HIPed at 950°F/15 ksi/6 hr. Initial radiographic Grade B, post-HIP Grade A.

5v3-2 (a) 5v3-2 (b) 5v3-2 (c)

Figure 18 SEM fractographs of A201-T7 tensile bar that failed at 57.7 ksi. Material was HIPed at 950°F/10 ksi/12 hr. Initial radiographic Grade B, post-HIP Grade B+/A-.



3v2-1 (a) 3v2-1 (b) 3v2-1 (c)

Figure 19. SEM fractographs of A201-T7 tensile bar that failed at 54.8 ksi. Material was HIPed at 950°F/10 ksi/12 hr. Initial radiographic Grade C, post-HIP Grade B/B+.

covered by porosity, and a eutectic phase that appears to have remelted during the HIP cycle is common to most of the surfaces exhibiting porosity. The third sample (Figure 16) exhibits a mixed fracture mode and, as would be expected, it showed fracture properties intermediate to the other two. The differences in microstructures exhibited in the three figures clearly demonstrates the variability in properties that is associated with eutectic phase melting. It is apparent that the variability is the result of HIP processing, since other factors are similar for the other Grade C material used in this study. The presence of the eutectic phase requires that processing temperatures be maintained at a minimum to reduce the potential for remelting of this phase.

Figures 20 and 21 show the influence of porosity on fatigue properties of HCF test bars. The fatigue failure shown in Figure 20 clearly originates at a pore in the sample. The presence of this pore significantly reduced the fatigue life. In contrast, the sample in Figure 19, shows no porosity. Initiation of this fatigue crack required a great deal of energy, as evidenced by the ductile region at the initiation site, and the absorption of this energy greatly retarded fatigue crack initiation.

The ability of a HIP cycle to completely close all porosity in a material is dependent on the severity of the porosity and on the HIP parameters. While all porosity has been removed from the test bar shown in Figure 16, another bar from the same HIP cycle (Figure 17) continues to show porosity along some grain boundaries. The difference between these two test bars is the radiographic grade (ie., amount of porosity) prior to HIP. This particular HIP cycle (950°F/10 ksi/12 hr) was unable to completely close all porosity in the initial Grade C material, but was adequate for initial Grade B material. Similar results were seen for

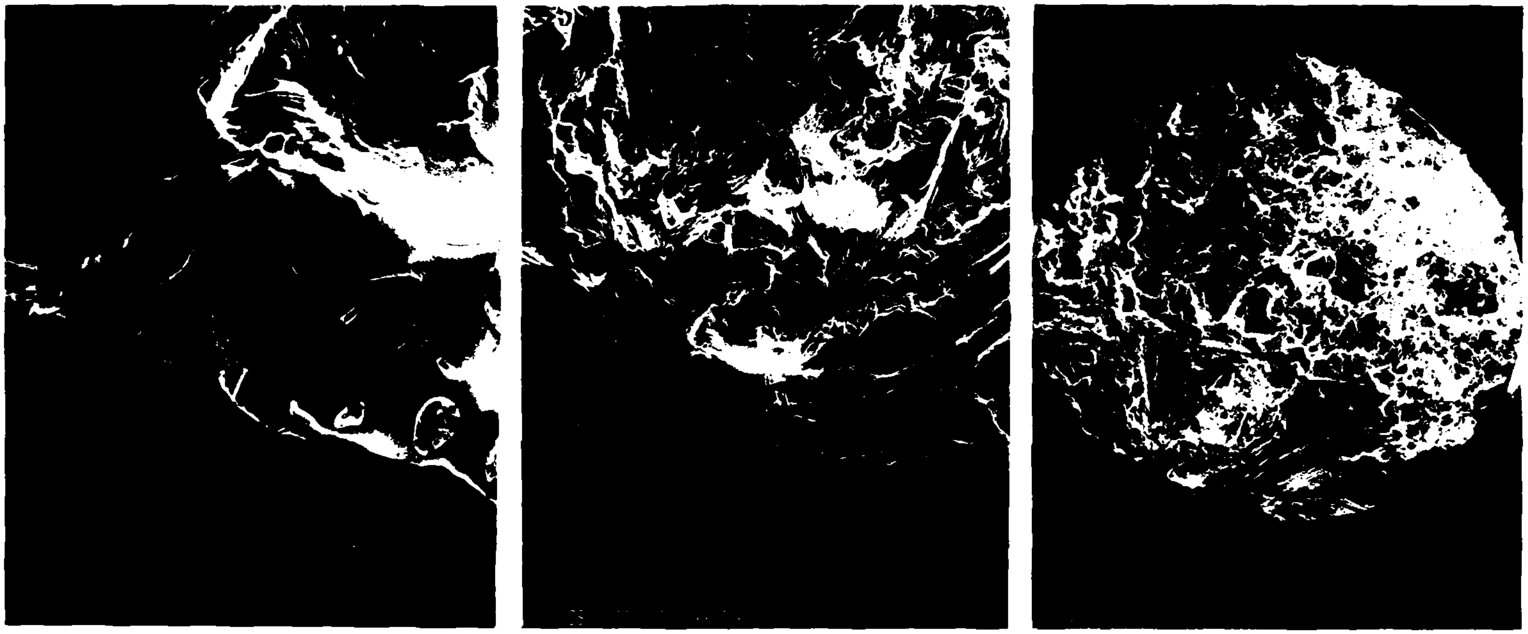


Figure 20. SEM fractographs of a typical HCF failure initiating at internal porosity remaining after HIP cycle. The material HIPed at 950°F/10 ksi/12 hr. The sample failed after 258,000 cycles at a 20-ksi stress level. Initial radiographic, Grade C, post-HIP Grade B/B+.

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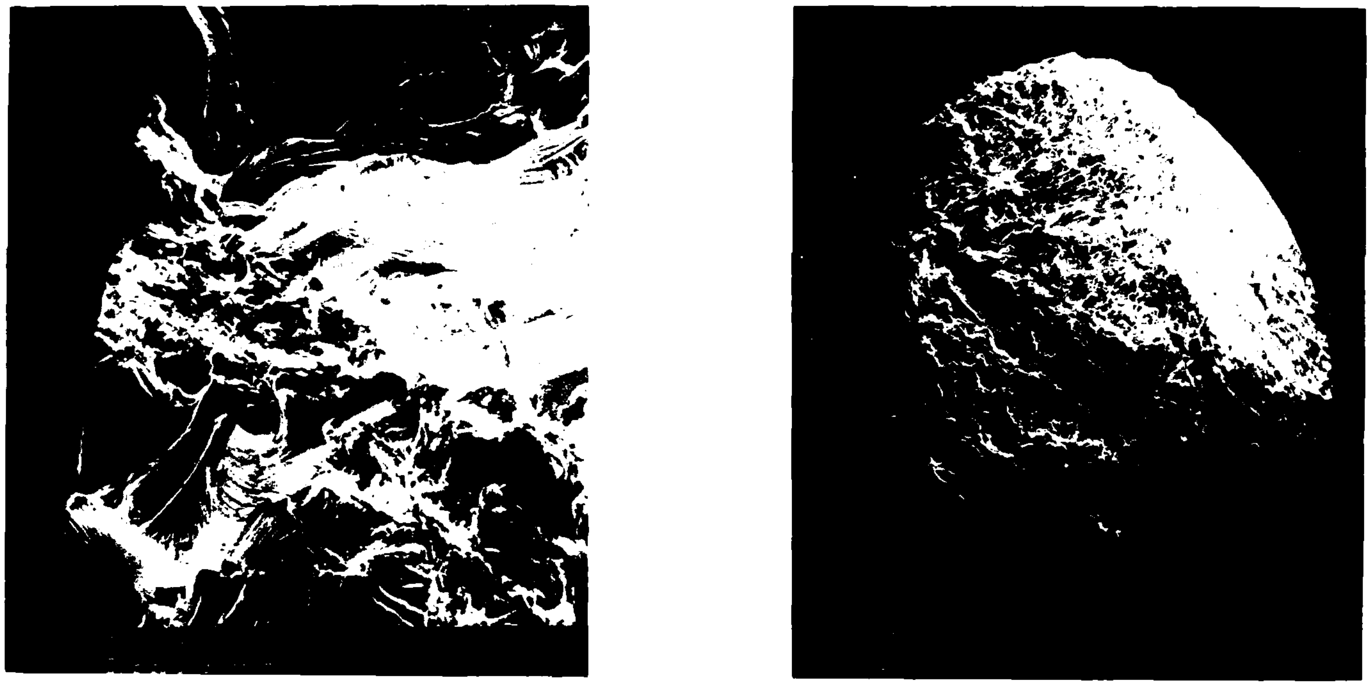


Figure 21. SEM fractographs of a typical HCF failure in a test sample exhibiting no internal porosity after HIP. The material was HIPed at 950°F/15 ksi/6 hr. The sample failed after 290,000 cycles at a 25-ksi stress level. Initial radiographic Grade B, post-HIP Grade A.

all HIP cycles investigated, with the exception of the 950°F/ 15 ksi/6 hr cycle. In this case, all materials HIPed were radiographic Grade A, regardless of initial grade. The results indicate that 10 ksi is inadequate pressure for full densification of the material within the time and temperature limitations evaluated. A pressure of 15 ksi, however, will provide superior material integrity while maintaining temperature sufficiently below that at which eutectic melting becomes a factor.

4.2 Mechanical Property Testing

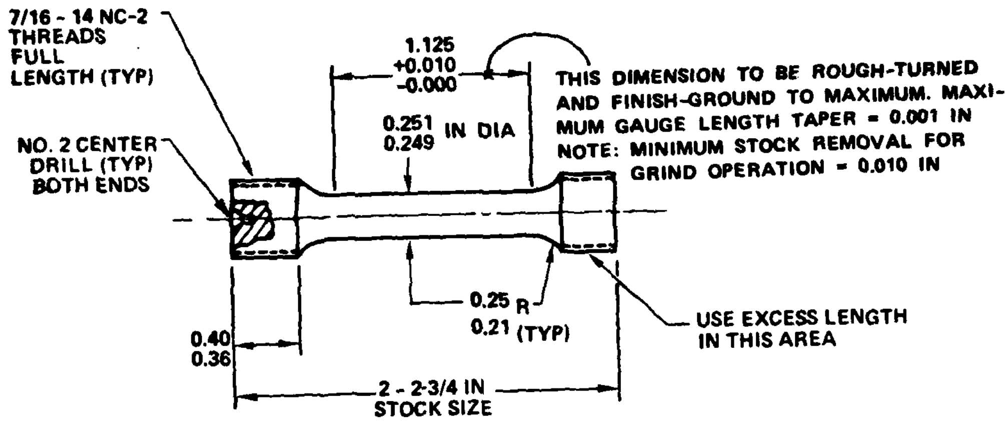
Tensile and HCF tests were used to assess HIP cycle influence on material properties. The tensile tests were conducted at Joliet Metallurgical Laboratories, Inc., Joliet, IL. The HCF testing was performed by Metcut Research Associates, Inc., Cincinnati, OH. All tests were conducted per standard ASTM procedures.

4.2.1 Specimen Preparation

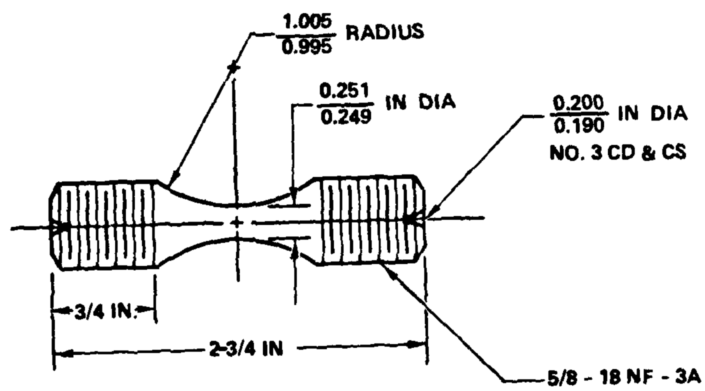
Following the T7 heat treatment, test bars for mechanical property evaluations were prepared. Cylindrical slugs, 3.5 inches long by 0.5 inches in diameter, were taken from the rim sections by electrical discharge machining (EDM). A total of 142 slugs were obtained. The tensile and HCF slugs then were machined per the specifications shown in Figure 22.

4.2.2 Tensile Testing

Room temperature tensile tests were conducted on material from each HIP run and on several sections of as-cast material (Grade C). A summary of the test results is shown in Table 6 and Figure 23. The range bars (Figure 23) indicate data scatter and



(a)



(b)

Figure 22. Mechanical test specimens used in this program: (a) tensile bar, (b) HCF bar.

TABLE 6. TENSILE TEST RESULTS FOR HIPed A201-T7 MATERIAL

HIP Cycle, °F/ksi/hr	Radiographic Grade (Initial)	Ultimate Tensile Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation in 4D, %	Reduction in Area, %
As-Cast	C	33.7	*	1.7	1.5
		35.0	*	1.6	1.4
		37.3	*	2.2	1.5
		29.6	*	1.6	1.4
		11.1	*	1.6	0.9
		23.0	*	1.2	1.2
950/10/6	B	51.6	50.2	2.2	3.7
		60.2	52.4	8.3	15.1
		63.2	54.7	11.1	16.5
		58.6	52.8	4.7	7.6
		58.5	52.2	2.7	5.5
		62.1	35.9	8.9	10.7
950/10/6	C	24.7	*	1.2	1.5
		46.6	*	1.7	1.6
		43.2	*	0.7	1.5
		20.1	*	1.6	1.5
		21.6	21.4	1.6	1.6
		25.2	*	2.2	1.4
950/15/6	B	63.1	54.6	6.2	9.2
		64.2	55.6	5.7	8.4
		61.8	54.3	5.5	5.3
		61.9	51.4	8.7	11.7
		59.6	49.5	8.6	15.3
		34.6	*	1.6	3.1
		60.7	52.2	5.7	10.0
		60.1	48.7	10.8	18.9
		60.8	50.4	6.5	7.8
		63.1	55.2	11.1	18.1
		62.3	54.3	9.0	15.8
		62.2	54.9	9.9	18.7
		60.6	53.5	6.8	15.8
		61.6	54.3	7.6	12.9
950/15/6[(1)]	B	62.1	53.1	8.4	15.1
		60.0	50.4	8.3	11.2
		62.2	51.4	10.9	18.6
		60.6	50.8	13.9	31.2
950/15/6	C	42.0	40.2	2.1	2.3
		43.5	39.9	2.5	2.8
		42.0	39.7	1.8	2.3
		63.2	54.0	6.9	6.8
		63.2	54.0	6.7	11.7
		62.6	52.8	7.5	10.7

*Specimen failed before reaching yield

(1) Heat Treatment Schedule 5b from Table 5, Section 3.3

TABLE 6. TENSILE TEST RESULTS FOR HIPed A201-T7 MATERIAL (Continued)

HIP Cycle, °F/ksi/hr	Radiographic Grade (Initial)	Ultimate Tensile Strength, ksi	0.2% Offset Yield Strength, ksi	Elongation in 4D, %	Reduction in Area, %
950/15/6	C	63.4	53.1	8.1	15.3
		59.1	48.1	10.1	11.6
		61.0	48.9	11.6	15.4
		62.7	52.2	10.7	16.8
		63.6	52.8	10.5	16.0
		59.0	46.6	11.0	16.7
		56.9	46.0	5.8	6.0
950/15/6 (1)	C	62.1	49.6	10.6	12.8
		62.1	48.9	12.2	15.0
		59.4	49.7	8.3	11.3
		60.8	49.4	9.0	12.1
		60.5	49.1	10.9	22.1
980/10/6	B	48.7	*	2.0	2.8
		14.3	*	1.3	1.4
		54.0	*	0.7	1.5
		6.4	*	0.2	**
		60.0	53.1	4.6	4.0
		33.9	*	0.2	**
980/10/6	C	32.6	*	1.2	0.7
		34.0	*	1.9	1.7
		25.8	*	1.5	1.5
		45.4	*	1.7	2.2
		43.7	*	1.5	2.3
		44.2	*	1.9	2.2
950/10/12	B	49.9		2.7	3.5
		57.7	53.8	3.8	4.6
		41.3	*	0.7	1.5
		47.3	46.9	2.0	3.0
		48.8	47.6	2.5	3.7
		47.9	46.8	1.7	3.0
950/10/12	C	47.5	*	2.0	2.5
		46.1	*	1.8	0.9
		46.5	*	2.3	2.4
		54.8	54.1	2.7	3.7
		50.4	*	2.0	1.4
		53.1	*	2.3	3.8

*Specimen failed before reaching yield

**Specimen failed in fillet, precluding reduction in area measurement

(1) Heat Treatment Schedule 5b from Table 5, Section 3.3

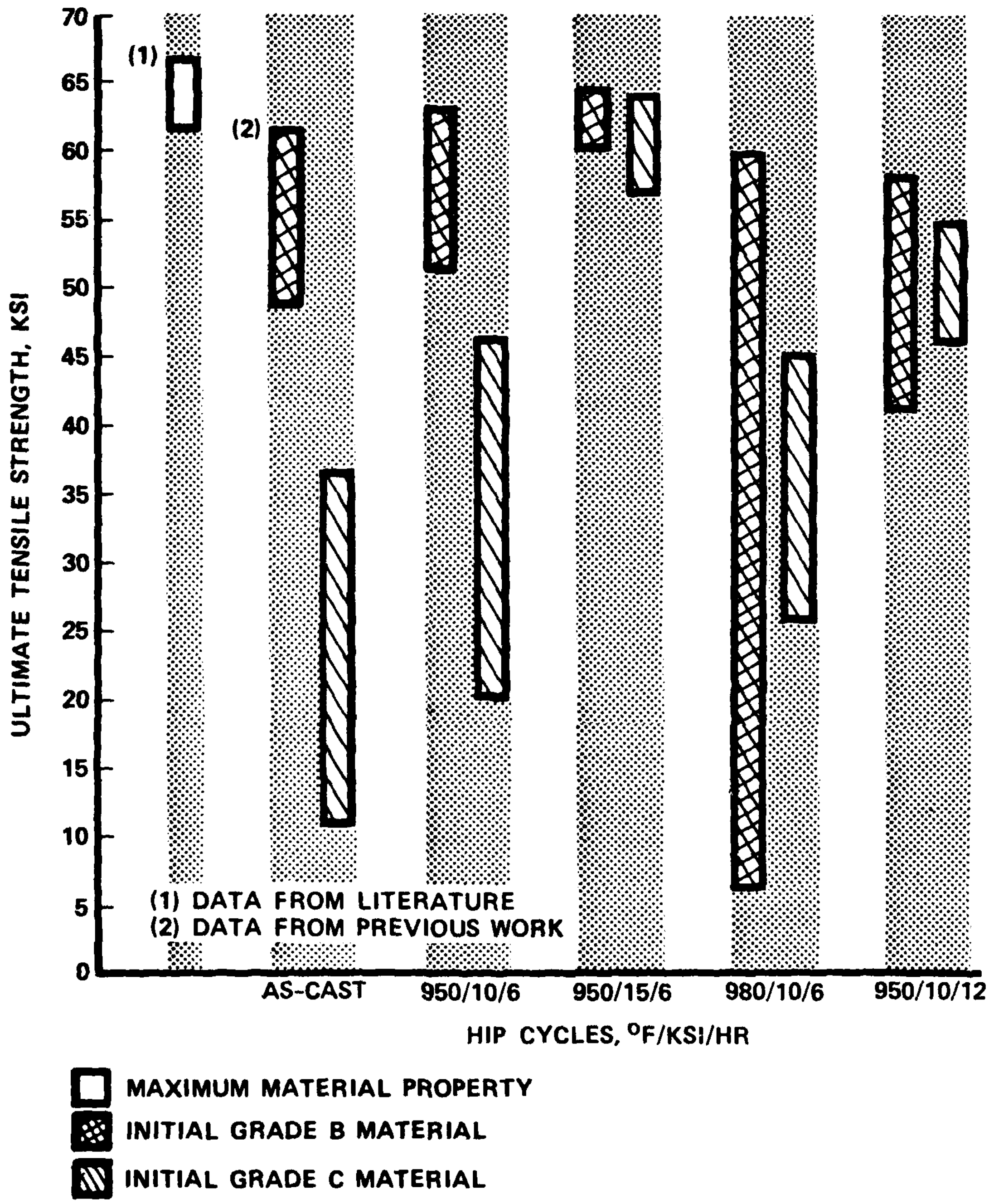


Figure 23. Ultimate tensile strength (UTS) range for A201-T7 material after HIP.

are corrected by statistics only in the case of the 950°F/15 ksi/ 6 hr HIP cycle because this was the only condition for which sufficient tests were conducted to provide a reliable statistical analysis. Table 7 shows the results of the statistical analysis conducted. It is apparent that only the 950°F/15 ksi/6 hr HIP cycle provided significant improvements in tensile properties. As shown in Figure 23, the ultimate tensile strength (UTS) of this material is equivalent to the maximum material strength determined for sound material with no internal defects. The data scatter seen for the initial Grade B material is slightly less than for the initial Grade C material (standard deviation is 1.2 vs 2 ksi) but both are significantly smaller than all other test groups. The data analysis shows no statistical difference between the two radiographic grades following HIP processing. In addition, no difference was seen in the material from the two solutionizing treatments.

The three HIP cycles conducted at 10 ksi stress provided only marginal improvements that are not totally consistent. Slight differences in tensile strength and data scatter can be related to individual differences in the sample groups tested. A statistical evaluation of these samples was not possible since too few samples were available for a reliable analysis. The most glaring inconsistency is the wide range of tensile strengths obtained in the initial Grade B material processed in the 980°F/10 ksi/6 hr HIP cycle. The UTS data spans the range of 6 to 60 ksi. As was noted in Section 4.1, the variation can be related to eutectic melting during the HIP cycle. The fact that the initial Grade B material did not exhibit the same melting phenomenon can only be attributed to a difference in the homogeneity of the specific casting used for the test bars.

The data also indicates an improvement in tensile properties of the initial Grade C material with increased time in the HIP

TABLE 7. STATISTICAL ANALYSIS RESULTS FOR TENSILE TEST DATA*

HIP Cycle (°F/ksi/hr)	Initial Grade B Average UTS, ksi	Initial Grade B Standard Deviation	Initial Grade C Average UTS, ksi	Initial Grade C Standard Deviation
950/10/6	59.0	4.1	30.2	11.8
950/15/6	61.6	1.2	61.3	2.0
980/10/6	36.2	22.0	37.6	8.0
950/10/12	48.8	5.3	49.7	3.6
As-Cast	-	-	28.3	9.8

*Insufficient data was available to establish reliability of this statistical analysis with the exception of the 950°F/15 ksi/6 hr data

cycle. The improvement can be related to the longer time, which allows additional opportunity for diffusional transport and plastic flow around the large holes. Despite the marginal improvements seen in the increased time condition, the failure of the HIP cycle to produce tensile properties equivalent to those of the sound material indicates only partial closure of the internal porosity. This conclusion is consistent with the radiographic inspection results since some of the test bars attained radiographic Grade A while others remained Grade B after HIP.

4.2.3 High Cycle Fatigue (HCF) Testing

Room temperature HCF tests were conducted on as-cast material and on material from each HIP cycle. The data is shown in Figure 24 and Table 8. The tests were conducted on a calibrated Sonntag SF-1-U rotating mass type universal fatigue machine. The loading was axial and supplied at a constant sinusoidal waveform of 30 Hz frequency. The stress ratio, A, (alternating stress/mean stress), was 0.95.

Statistical evaluations of all HCF data provided a clear understanding of the results, as shown in Figure 24. It was concluded that the data could be grouped by final radiographic grade, regardless of the processing used to obtain that level. Therefore, the data on Figure 24 are shown by Grades A, B, and C rather than by HIP cycle. The heat treatment modification also did not influence the material properties; therefore, all the data could be grouped together.

The most significant result observed in the HCF testing is seen in the considerable improvement in HCF properties associated with the radiographic quality improvement from Grade B to A. The 10 million cycle endurance limit is increased from ~16 ksi to ~24

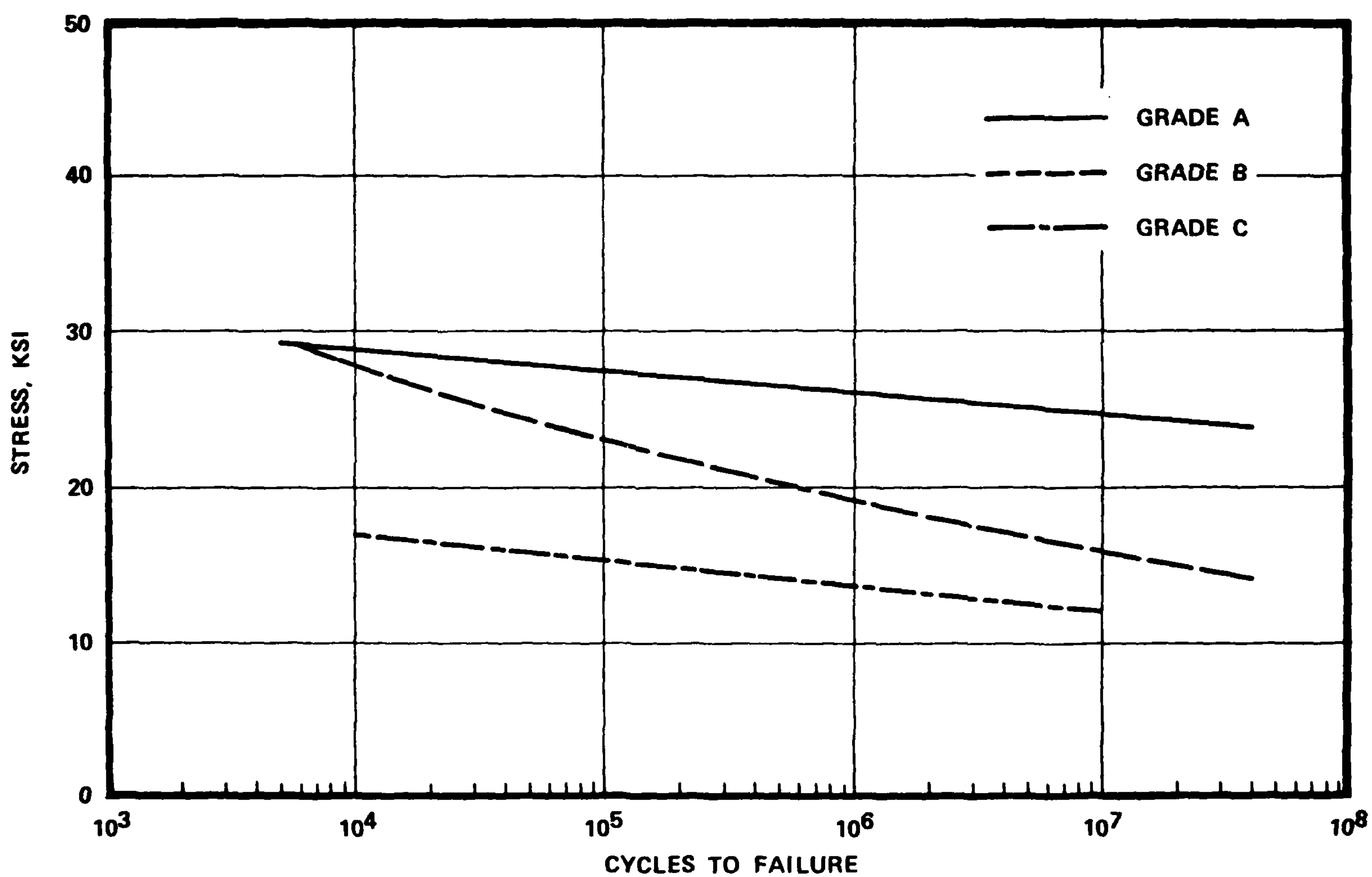


Figure 24. A201 aluminum HCF properties for final grade A and B (HIPed) materials and Grade C (as cast) materials.

TABLE 8. HCF TEST RESULTS FOR HIPed A201-T7 MATERIAL

HIP Cycle, °F/ksi/hr	Radiographic Grade (Initial)	Stress, ksi	Cycles to Failure
As Cast	C	12.5	On Loading
		15.0	107,000
		20.0	On Loading
		25.0	2,000
950/10/6	B	18.0	276,000
		18.0	10,636,000*
		20.0	6,593,000
		25.0	594,000
950/10/6	C	15.0	10,268,000*
		20.0	95,000
		25.0	73,000
		30.0	27,000
950/15/6	B	20.0	56,000
		20.0	10,378,000*
		25.0	290,000
		25.0	10,091,000*
		25.0	10,151,000*
		26.0	349,000
		27.0	4,108,000
		27.0	470,000
		30.0	250,000
		30.0	63,000
		30.0	17,000
950/15/6 (1)	B	20.0	10,149,000*
		22.0	10,004,000*
		23.0	4,730,000
		25.0	2,033,000
950/15/6	C	20.0	10,312,000*
		23.0	5,616,000*
		25.0	10,455,000*
		25.0	10,006,000*
		25.0	10,402,000*
		25.0	181,000
		27.0	5,472,000
		27.0	423,000
		27.0	78,000

*Specimen ran out without failure.

(1) Heat treatment schedule 5b from Table 5, Section 3.3

TABLE 8. HCF TEST RESULTS FOR HIPed A201-T7 MATERIAL (Contd)

HIP Cycle, °F/ksi/hr	Radiographic Grade (Initial)	Stress, ksi	Cycles to Failure
950/15/6	C	28.0	1,083,000
		30.0	4,339,000
		30.0	10,071,000*
		30.0	2,830,000
		33.0	2,423,000
		35.0	3,639,000
		45.0	244,000
950/15/6 (1)	C	20.0	10,288,000*
		25.0	30,000
		25.0	6,242,000
		30.0	30,000
980/10/6	B	20.0	500
		20.0	10,056,000*
		25.0	125,000
		30.0	2,000
980/10/6	C	15.0	376,000
		20.0	86,000
		25.0	45,000
		25.0	500
950/10/12	B	17.5	587,000
		20.0	1,986,000
		25.0	638,000
		30.0	On Loading
950/10/12	C	15.0	468,000
		20.0	258,000
		25.0	34,000
		27.5	71,000

*Specimen ran out without failure.

(1) Heat treatment schedule 5b from Table 5, Section 3.3.

ksi. The results indicate that closing of the small holes allowable in a Grade B casting will greatly retard fatigue crack initiation. From this study, it appears that crack initiation is the rate controlling step in fatigue failure of A201 aluminum castings.

While the processing procedures used to arrive at the Grade A final condition were shown to be unimportant, relative to properties, it should be noted that only one sample from a HIP cycle other than the 950°F/15 ksi/6 hr run was included in the Grade A material property summary (Figure 24). In contrast, only one of the eleven front frame sections HIPed at 950°F/15 ksi/6 hr failed to be classified as Grade A; and this single piece was Grade B/B+. The obvious conclusion from the HCF testing is that the 950°F/15 ksi/6 hr HIP cycle offers the greatest improvements in fatigue properties.

4.3 Chemical Analysis

Bulk chemical analyses were conducted to ascertain that the test material met specified chemistries for A201 aluminum. The results of analyses from two randomly selected test bars are shown in Table 9. All elements were within specified limits with the exception of the titanium in the first section. The titanium content was 0.04 weight percent above the specification limit. It is the opinion of Garrett and Conalco materials personnel that this deviation is insignificant and did not influence program results.

A hydrogen content analysis also was performed. As-cast and HIPed materials were compared to ascertain that the HIP processing did not introduce any hydrogen, which could significantly alter mechanical properties. Table 10 shows the results of the analyses. The increase of 4 ppm is not significant and did not influence properties.

TABLE 9. BULK CHEMICAL ANALYSES OF A201-T7 MATERIAL USED IN THIS PROGRAM

Element	Specification (EMS 54027)	First Section	Second Section
Cu	4.0 - 5.0	4.4	4.2
Ag	0.40 - 1.0	0.54	0.48
Mg	0.20 - 0.35	0.21	0.24
Ti	0.15 - 0.35	0.39	0.34
Mn	0.20 - 0.35	0.20	0.20
Fe	0 - 0.10	0.03	0.03
Si	0 - 0.05	0.03	0.02
Other (Zn, B, Ni, Cr, Be)	0 - 0.03	0	0

TABLE 10. HYDROGEN ANALYSES OF AS-CAST AND HIP PROCESSED A201 MATERIAL

Section No.	Hydrogen Content, ppm	Material Condition
1v3	2	As-cast
2v8	6	After HIP+T7 Heat Treat

5.0 CONCLUSIONS

Conclusions derived from an analysis of the completed program results are as follows:

- HIP processing can significantly reduce porosity in A201 aluminum castings by closing and sealing internal voids

- The HIP parameter that most strongly influences material properties in A201 aluminum castings is pressure

- Increasing the time and/or temperature of the HIP cycle can provide slight improvements in mechanical properties

- A 950°F/15 ksi/6 hr HIP cycle can improve radiographic Grade C material (based on internal porosity) to Grade A

- If a HIP temperature greater than 965°F is used, the eutectic phase located along many grain boundaries can remelt and adversely affect mechanical properties of A201 aluminum castings

- The tensile strength of A201 material processed in a 950°F/15 ksi/6 hr HIP cycle is equivalent to the maximum material property, regardless of the initial radiographic quality (based on internal porosity)

- The HCF endurance limit of radiographic Grades B or C A201 aluminum castings can be raised by 8 to 12 ksi by HIPing at 950°F/15 ksi/6 hrs

- Reducing the standard solution anneal time used on the Garrett ATF3-6 turbofan engine front frame by 70 percent had no impact on mechanical properties of HIP processed material

- Ultrasonic inspection techniques show no potential application for inspection of A201 aluminum castings because grain size and surface roughness result in perturbations in signal output; the apparent defects indicated have no correlation with X-ray results